COMPLETION REPORT

SIMULATION OF SELENIUM DISCHARGE FROM SUBSURFACE DRAINAGE SYSTEMS

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SIMULATION OF SELENIUM DISCHARGE FROM SUBSURFACE DRAINAGE SYSTEMS

SUMMARY OF FINDINGS

Selenium, salinity and sodium concentrations were measured in a collapsed drift geologic formation to assess the potential impact of the soil chemical components on return flow water quality from the proposed Lake Andes-Wagner Irrigation Project in south central South Dakota. Soil samples were collected from 0.0-0.5, 0.5-1.0, 1.0-2.0 and 2.0-3.0 m depths every 200 m along a 26.7-km transect. No trends were detected in the magnitude of chemical concentrations along the transect. Spatial correlation (structure) was found to occur for sodium adsorption ratio (SAR) values with distances of 500 m or less and for selenium and salinity parameters at soil sample spacings of 200 m or less. Selenium concentrations tend to be similar and the highest for the 1.0-2.0 m and 2.0-3.0 m depths while the 0.0-0.5 m depth contains the smallest concentrations. Mean total selenium concentrations are 894, 965, 1346 and 1674 ppb for the four soil depths. Readily available selenium is about 8 % of the total selenium in the top 0.5 m soil layer, 22 % in the 0.5-1.0 m layer, 37 % in the 1.0-2.0 m layer and 38 % in the 2.0-3.0 m layer. Log normal probability density functions can be used to describe selenium concentrations and profile SAR values for the soil. Soil profile electrical conductivity values can be described by a normal probability function.

A two parameter Gamma Distribution Function was used for the development of a transfer function to describe the discharge of selenium from a single subsurface drain line. Relationships were developed for the two parameters of the Gamma Function and geometries of subsurface drainage systems. The frequency of drain line spacings anticipated for the Lake Andes-Wagner Project area was defined by a log normal probability density function. A Monte Carlo simulation was then used to obtain an estimate of selenium discharge from a region that contains a variety of drain line spacings. The basic assumption associated with the simulation results is that piston or bulk water flow controls the movement of selenium to the drain line and the influence of diffusion, dispersion and soil reactions are not important. Recent drainage literature shows that water moves along preferential flow paths through the soil and not as piston type flow; however, techniques for the quantification of preferential flow are not available. Likewise, the role of diffusion, dispersion and chemical reactions in the soil need to be defined before accurate estimates of selenium discharges from subsurface drainage systems are possible.

Draft copies of two technical manuscripts "Selenium and salinity distributions in a glacial till soil" and "Selenium concentrations in subsurface drainage water" are enclosed and are being used as the body of this completion report.

SELENIUM AND SALINITY DISTRIBUTIONS IN A GLACIAL TILL SOIL

by

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ABSTRACT

Selenium, salinity and sodium concentrations were measured in a collapsed drift geologic formation to assess the potential impact of the soil chemical components on return flow water quality from a proposed irrigation project in the area. Soil samples were collected from 0.0-0.5, 0.5-1.0, 1.0-2.0 and 2.0-3.0 m depths every 200 m along a 26.7-km transect. No trends were detected in the magnitude of chemical concentrations along the transect. Spatial correlation (structure) was found to occur for sodium adsorption ratio (SAR) values with distances of 500 m or less. Weak spatial structures were found for the other soil chemical parameters at soil sample spacings of more than 200 m. Chemical concentrations tend to be similar and the highest for the 1.0-2.0 m and 2.0-3.0 m depths while the 0.0-0.5 m depth contains the smallest concentrations. Log normal probability density functions can be used to describe selenium concentrations and profile SAR values for the soil. Soil profile electrical conductivity values can be described by a normal probability function.

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INTRODUCTION

The Lake Andes-Wagner (hereafter called LAW) project is a proposed 16,000-ha, irrigation project in south central South Dakota. The project area is located adjacent to and east of the Missouri River where the River becomes the border between Nebraska and South Dakota.

Soils investigations in the LAW project area by Breitzman (1990) and Wilson et al. (1990) found selenium concentrations similar to those in the San Joaquin Valley of California where major environmental problems were detected. In addition, earlier drainage needs investigations of the project area (Department of the Interior, 1985) indicate that most of the irrigated lands will require subsurface (closed) drains to provide adequate subsurface drainage under sustained irrigated conditions. Thus, there is concern about the possibility of elevated selenium concentrations occurring in drainage water from the LAW project if it is constructed. Current data sets provide insight into the range of selenium concentrations that can be encountered in the field but the soil samples were taken in such a manner that is impossible to quantify the spatial variability of selenium in the project area and to extend the application of the data sets beyond the specific sample sites.

A systematic survey of chemical soil properties, that could possibly adversely affect the quality of irrigation return flows, was conducted in the LAW project area during 1993 and 1994. The survey was intended to provide information about the existence of areas within the proposed project boundaries where chemical concentrations could preclude subareas from irrigation development.

The objectives of the study were to
1. Assess the spatial distribution of selenium, salinity and sodium in Lake Andes-Wagner area soils,
2. Investigate the spatial statistics (structure) of selenium, salinity and sodium in the soils and
3. Identify probability density functions to describe the selenium, salinity and sodium data sets.

EXPERIMENTAL PROCEDURE

Classification of the surficial glacial drift from the late Wisconsin ice advance is illustrated in Figure 1. Most of the area has been classified as till or collapsed drift (Breitzman, 1990). One orthogonal transect was positioned in the till area west of

Choteau Creek and a second was located east of Choteau Creek in the collapsed drift area. The data presented in this paper are from the soils in the collapsed drift transect (Transect B). Soil samples were collected at sites every 200 m along the 16.7-km north and south leg and the 10-km east and west leg of the transect.

Four soil sample depths were used in the investigation; 0.0-0.5 m, 0.5-1.0 m, 1.0-2.0 m and 2.0-3.0 m. Soil samples were collected with a Giddings probe and a 7.6-cm core tube to a depth of 1.0 m. A 5.1-cm core tube was used to the 2.0-m depth and a 4.1-cm core tube down to the 3.0-m depth.

Selenium (Se) concentration analyses were grouped into three operationally defined fractions (Chao and Sanzolene, 1989). Available Se and conditionally available Se were extracted from the same soil sample. Available Se is defined as 0.1 M KH_2PO_4 extractable. This includes the H_2O soluble and nonspecifically adsorbed selenate and the exchangeable, specifically adsorbed selenite. Conditionally available Se is defined as 4M HCL extractable. This is the Se associated with oxide minerals (Fe, Mn and Al), amorphous minerals, carbonates, acid-volatile sulfides and acid-hydrolyzable organic matter. The Se in this fraction is not readily available; however, it has the potential to become available with changes in pH or redox. Total Se was determined from a separate sample using a mixed acid digestion (Briggs and Crock, 1986). Unavailable Se was calculated as the difference between total Se and the sum of the available and conditionally available Se.

Electrical conductivity (EC) values were determined by a method presented by Rhodes (1982). Likewise, sodium adsorption ratio (SAR) values were determined by standard laboratory methods given by Rhodes (1982) and Richards (1954).

Spatial statistics (geostatistics) of the soil chemical parameters were determined with the aid of GEO-EAS 1.2.1 computer program (Englund and Sparks, 1991). Probability density function analyses were conducted in accord with the procedures suggested by Haan (1977). D'Agostino's (1971) statistical test was used at a 10 % significance level to evaluate whether a given probability density function could be used to represent a chemical data set. D'Agostino's test compliments the Sharpio-Wilkens test and can be used for data sets with more than 50 observations but less than 1000 (Parkin and Robinson, 1992).

Statistical analyses were performed on each of the four soil sample depths. Composite soil profile values were represented by a depth weighted average of the individual depth concentrations.

RESULTS

Selenium

No general trends were detected for Se concentrations along the north to south leg of the transect in the collapsed drift area. Readily available and conditionally available Se concentrations for the 3-m soil profile along the transect leg are presented in Figures 2 and 3. Large variations in readily available Se concentrations are common between adjacent sample sites; the readily available values appear to be random in space along the transect. Conditionally available Se concentrations are more uniform in magnitude than the readily available concentrations, but also appear to be randomly occurring in space.

A semi-variogram of the available Se data set for the 0.0-0.5 m soil layer indicates no spatial correlation between sample sites that are more than 500 m apart (Figure 4). Likewise, the semi-variogram for the conditionally available Se data set shows minimal correlation between sample sites that are more than 300 m apart (Figure 5). Note that log transformed data were used in Figure 4 but not in Figure 5. No correlation was found for total Se concentrations at a sample distances of 200 m or more. For practical purposes, no strong spatial correlations were found for all forms of Se in the top 0.5 m of the soil profile at distances greater than 200 m, the minimum soil sample spacing.

A summary of the Se analyses for the transect located in the collapsed drift area west of Choteau Creek (Figure 1) is presented in Table 1. Mean values for readily available Se increase from 71 ppb in the top 0.5 m to 634 ppb for the 2.0-3.0 m depth, a nine fold difference. A maximum value of 7,338 ppb was found for the 2.0-3.0 m depth. The mean value of 501 ppb for the 1.0-2.0 m depth is 133 ppb (21 %) less than 634 ppb mean value for the 2.0-3.0 m depth. Readily available Se concentrations for the 0.5-1.0 m depth are about three times larger than the values for the top 0.5 m.

Readily available Se mean values for the 0.0-0.5 m and the 0.5-1.0 m depths are about 22 % of the total Se mean values, while the ratio for the bottom two depths is about 38 %. This two value scenario is not representative of the conditionally available Se and total Se mean values. Conditionally available Se is about 30 % of the total Se for the top 0.5 m; however, the proportion is about 44 % for the bottom 2.5 m of the sampled soil profile. Conditionally available Se mean values range from 101 ppb for the 0.0-0.5 m depth and continuously increase with depth to a maximum of 735 ppb for the 2.0-3.0 m depth.

Unavailable Se mean values have less variation with depth than the other Se parameters; values range from 257 ppb for the top

depth to 305 ppb for the bottom depth. Unavailable Se means as a proportion of total Se means range from 49 % for the 0.0-0.5 m depth to about 20 % for the 1.0-3.0 m depths. In summary, soils in the 1.0-2.0 m and 2.0-3.0 m depths have similar mean Se concentration characteristics and the maximum Se concentrations, the top 0.5 m depth has the smallest Se concentrations and the Se concentrations for the 0.5-1.0 m depth are transitional between the top soil layer and the 1.0-3.0 m depths.

Large values of readily available Se tend to be associated with large values of total Se in the soil profile (Figure 6). A polynomial regression relationship of readily available versus total Se concentrations

Available Se = 0.162 (Total Se) + 0.0000924 (Total Se)**2

has an R squared value of 0.86. An upper bound for the data can be approximated by a line drawn through the origin with a slope of 0.75 which means that readily available Se is not more than 75 % of the total Se in the 3-m soil profile.

Log normal probability density functions can be used to describe Se concentration data sets for the collapsed drift area of the LAW project area. A histogram of readily available Se concentration values for the total 3.0-m profile is presented in Figure 7. Concentrations between 0 and 100 ppb (50 ppb bin) occurred most frequently and frequency of occurrence decreased with an increase in concentration values. Relative frequencies for a log normal based distribution are also presented in Figure 7. Statistical tests indicate that the field data set can be described by a log normal probability density function. Statistical tests also indicate that histograms of total profile concentration values for conditionally available Se (Figure 8), unavailable Se (Figure 9) and total Se (Figure 10) can be described by the log normal functions.

Salinity

Spatial distribution of 3-m EC values are shown in Figure 11. Again the values do not appear to follow a regular pattern and can be considered as random in nature.

The semi-variogram of EC values for the top 0.5-m of the soil profile shows no spatial structure or correlation for sample distances greater than 200 m (Figure 12).

A summary of the EC data sets for the collapsed drift area is presented in Table 2. Mean electrical conductivity values varied from 1.5 mmhos for the top soil depth to 6.1 mmhos for the bottom two depths. Again there is no apparent difference between the data sets for the 1.0-2.0 m and 2.0-3.0 m depths and the 0.5-1.0 depth is a transition depth between the top and lower depths. Minimum EC

values of 0.0 mmhos were found for all four sample depths and maximum values ranged from 11.1 to 15.4 mmhos.

It appears that a normal and not a log normal probability density function can best be used to mathematically describe the EC data sets for the collapsed drift area. The histogram for the total profile EC data set and relative frequency values for a normal distribution are illustrated in Figure 13. Similar results were found for the data sets associated with each of the four sample depths.

Sodium

Spatial distribution of the 3-m SAR values are presented in Figure 14. No general trend is evident in the data set.

Spatial correlation was detected for SAR values of soil sample sites that were less than 500 m apart (Figure 15). The semi-variogram indicates a nugget value of zero and a sill value 3.5.

Sodium adsorption ratio (SAR) values for the collapsed drift area are summarized in Table 2. Mean SAR values range from 2.3 for the top depth to 5.3 for the bottom depth. General trends for the SAR values are similar to the Se and EC data sets. The top 0.5 m contains the smallest SAR values, the bottom two sample depths contain SAR values that are statistically similar and the 0.5-1.0 m depth contains transitional SAR values between the top and bottom depths.

The histogram used to describe the SAR data set for the total soil profile can be described by a log normal probability density function (Figure 16). However, this is in contrast to data sets for the individual soil depths (data not shown) which do not follow the normal or the log normal distributions.

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TABLE 1. Summary of selenium concentrations in the collapsed drift area east of Choteau Creek.

DEPTH (m)	STAT. PARAMETERS	READILY AVAILABLE SELENIUM (ppb)	CONDITION. AVAILABLE SELENIUM (ppb)	UNAVAIL. SELENIUM (ppb)	TOTAL SELENIUM (ppb)
0.0-0.5	Mean	71	260	562	894
	Std. Dev.	153	101	257	336
	Data Range	0-1766	48-658	117-1918	227-2506
	Data Values	133	133	133	133
0.5-1.0	Mean	211	440	314	965
	Std. Dev.	417	272	237	631
	Data Range	0-2965	104-2283	0-1371	244-4426
	Data Values	133	133	133	133
1.0-2.0	Mean	501	567	278	1346
	Std. Dev.	740	410	604	1228
	Data Range	2-4313	74-2947	0-5321	220-7785
	Data Values	133	133	133	133
2.0-3.0	Mean	634	735	305	1674
	Std. Dev.	1073	525	305	1410
	Data Range	6-7338	83-3370	3-2042	159-8582
	Data Values	133	133	133	133
0.0-3.0	Mean	425	550	340	1316
	Std. Dev.	615	290	247	900
	Data Range	14-3912	112-1776	97-2133	271-5264
	Data Values	133	133	133	133

TABLE 2. Summary of electrical conductivities (EC) and sodium adsorption ratios (SAR) in the collapsed drift area east of Choteau Creek.

DEPTH (m)	STAT. PARAMETERS	ELECTRICAL CONDUCTIVITY (mmhos)	SODIUM ADSORPTION RATIO
0.0-0.5	Mean	1.5	2.3
	Std. Dev.	1.8	2.9
	Data Range	0-11.1	0-14.3
	Data Values	132	131
0.5-1.0	Mean	4.0	3.6
	Std. Dev.	2.8	3.3
	Data Range	0-11.8	0-15.8
	Data Values	127	122
1.0-2.0	Mean	6.1	5.1
	Std. Dev.	3.0	4.3
	Data Range	0-15.4	0-20.8
	Data Values	131	124
2.0-3.0	Mean	6.1	5.3
	Std. Dev.	3.0	4.4
	Data Range	0-14.7	0-19.2
	Data Values	129	127
0.0-3.0	Mean	4.9	4.3
	Std. Dev.	2.1	2.7
	Data Range	0-11.2	0-13.4
	Data Values	120	108

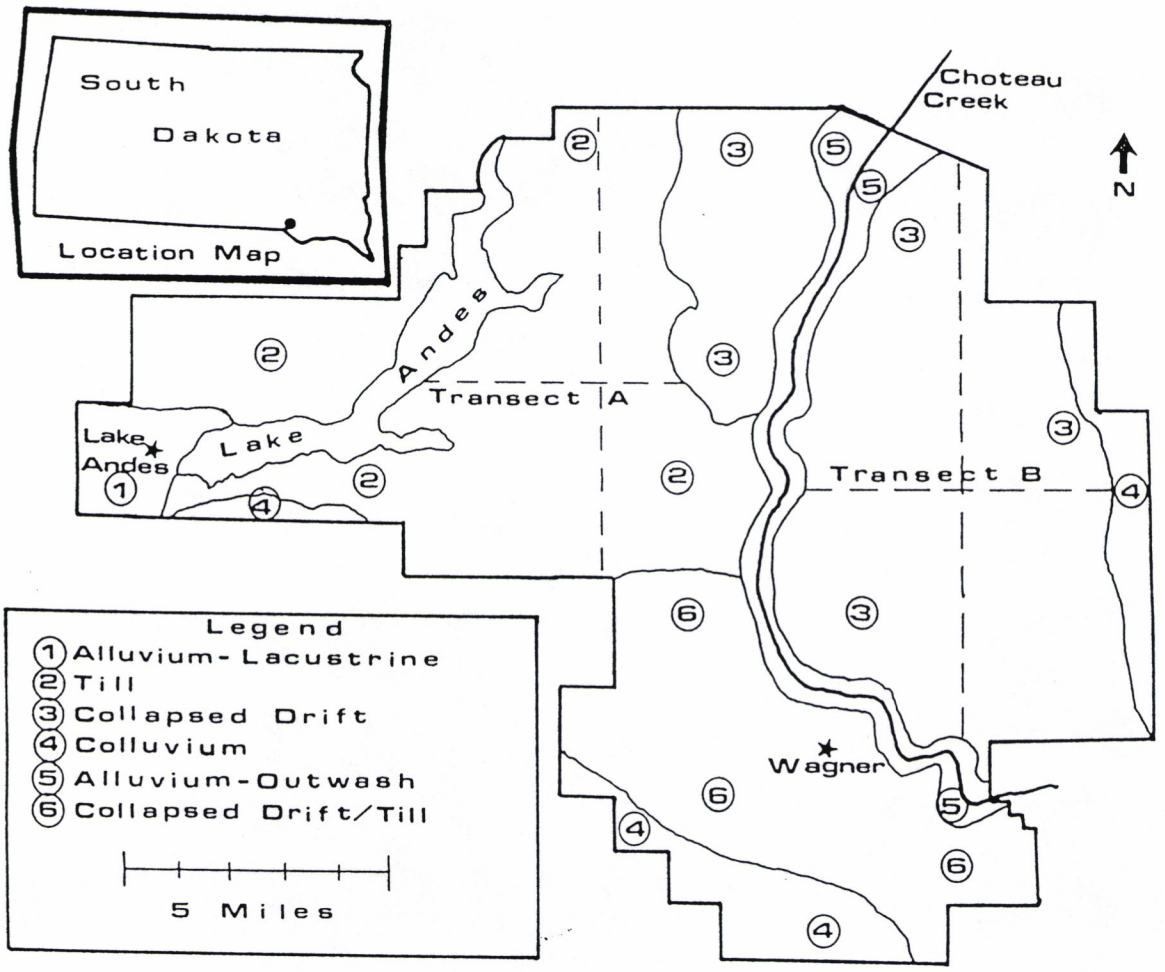

Figure 1. Location of the east transect (Transect B) in the Lake Andes-Wagner Project area used for the collection of soil samples.

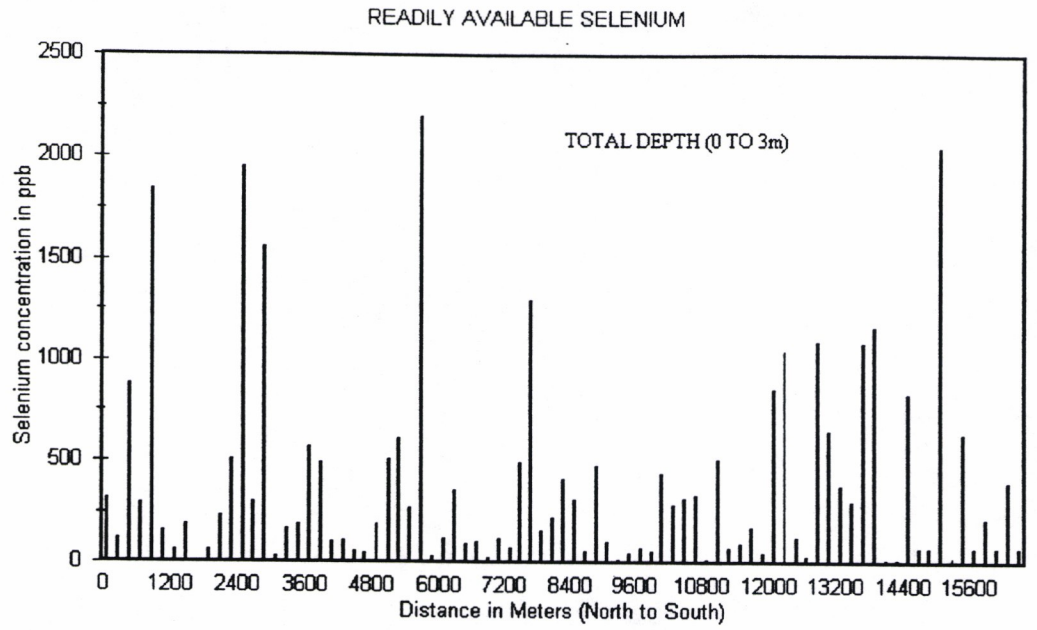

Figure 2. Readily available selenium concentrations (ppb) for the 3-m soil profile along the 16.7-km north to south leg of the transect in the collapsed drift area east of Choteau Creek.

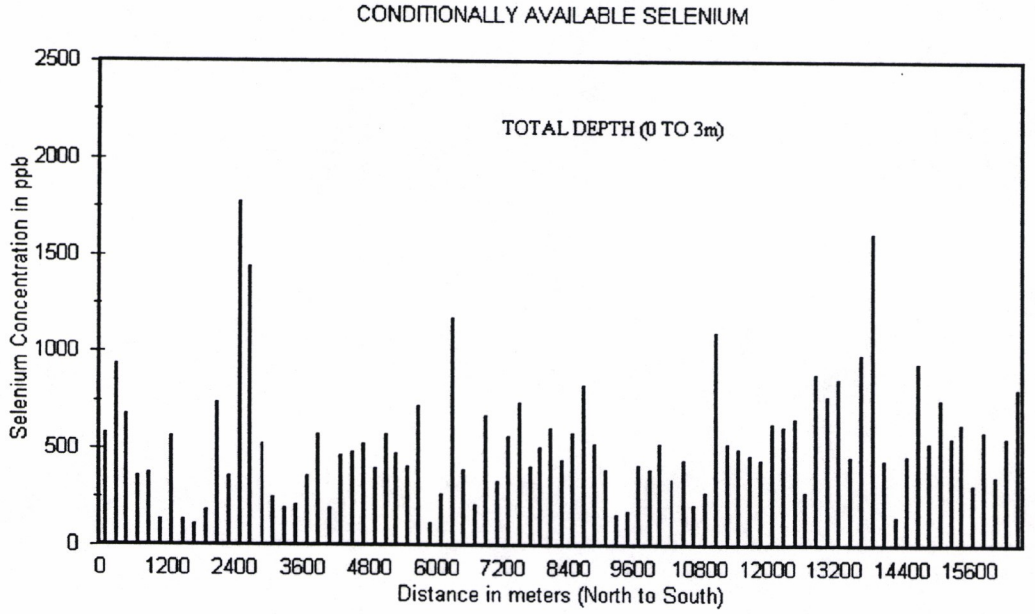

Figure 3. Conditionally available selenium concentrations (ppb) for the 3-m soil profile along the 16.7-km north to south leg of the transect in the collapsed drift area east of Choteau Creek.

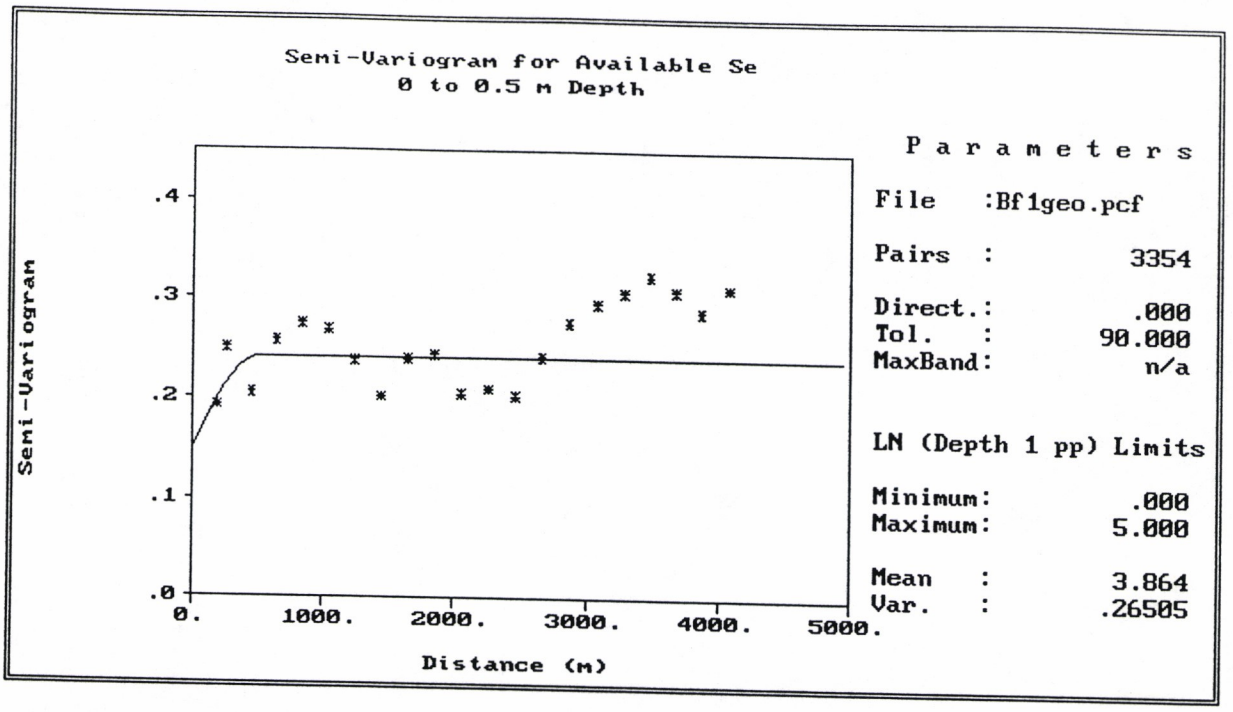

Figure 4. Semi-variogram for readily available selenium concentrations in the top 0.5 m depth of the collapsed drift east of Choteau Creek.

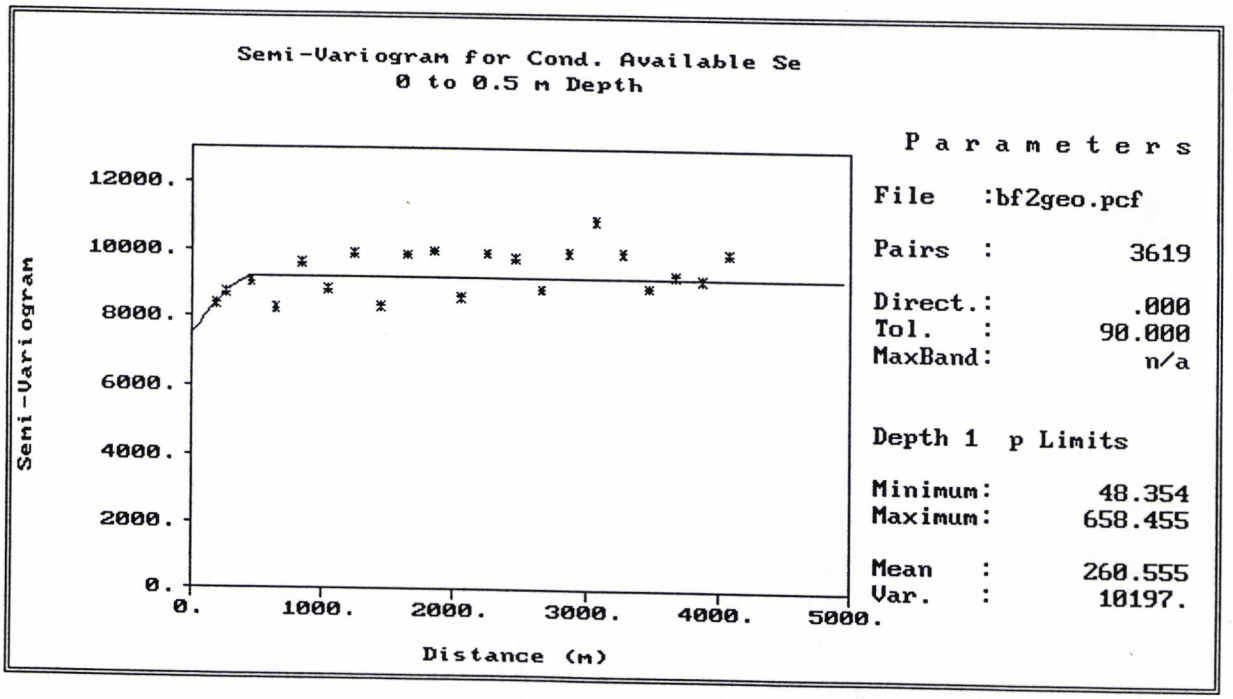

Figure 5. Semi-variogram for conditionally available selenium concentrations in the top 0.5 m depth of the collapsed drift east of Choteau Creek.

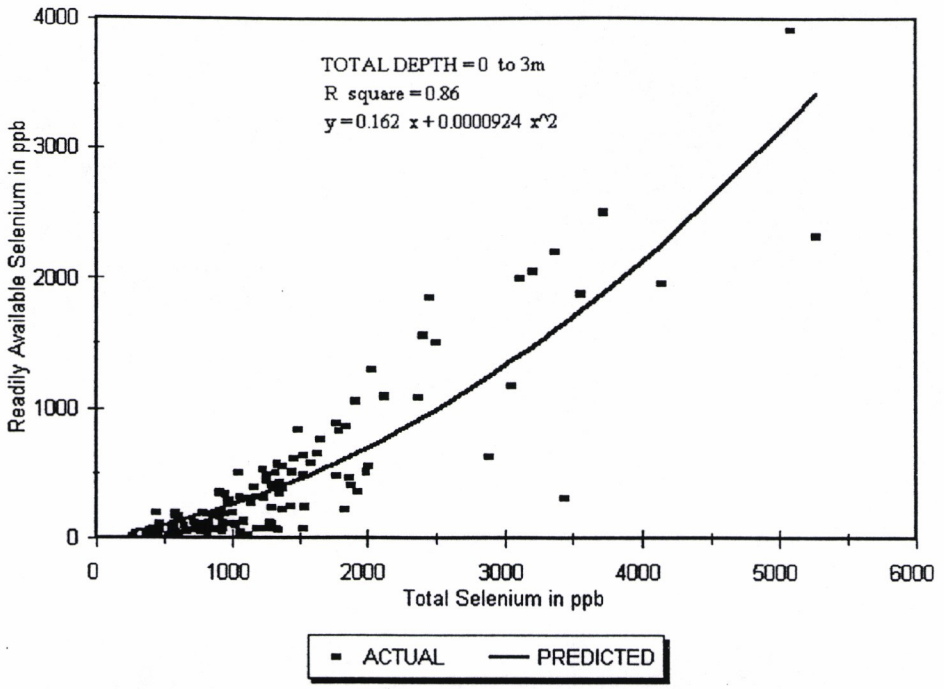
TOTAL DEPTH = 0 to 3m
R square = 0.86
y = 0.162 x + 0.0000924 x^2
Readily Available Selenium in ppb
Total Selenium in ppb
ACTUAL
PREDICTED

Figure 6. Plot of readily available selenium concentrations versus total selenium concentrations for the 3-m soil profile.

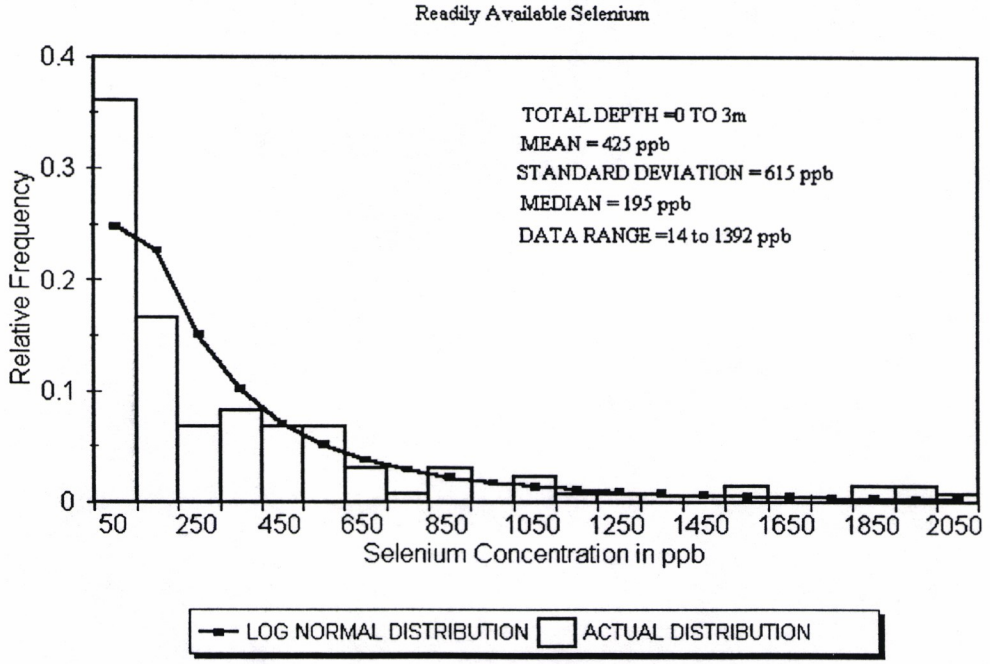

Figure 7. Relative frequency distributions for the 3-m profile, readily available selenium data set and the representative log normal probability density function.

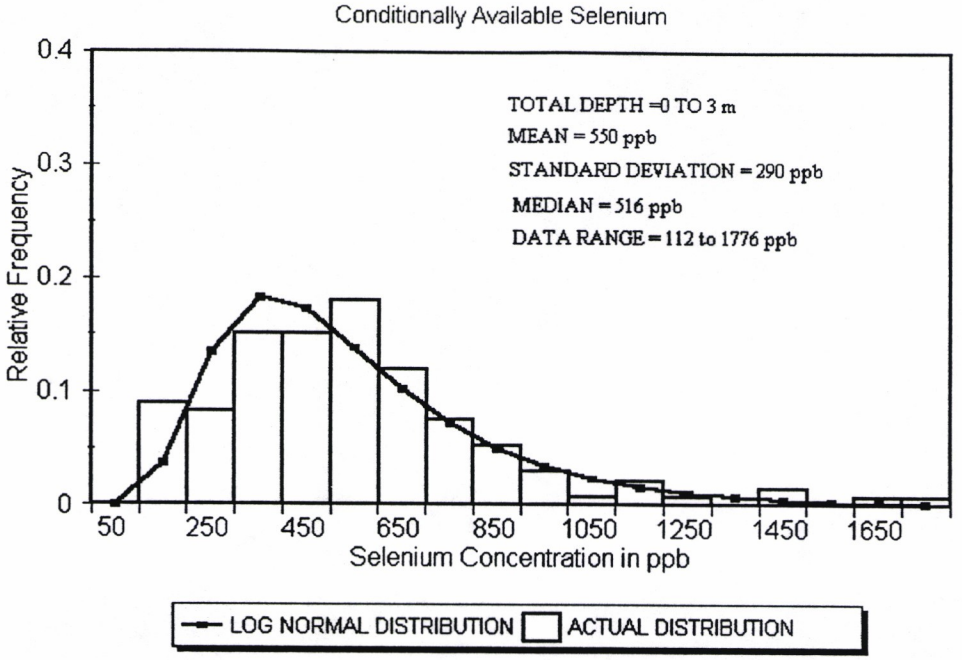

Figure 8. Relative frequency distributions for the 3-m profile, conditionally available selenium data set and the representative log normal probability density function.

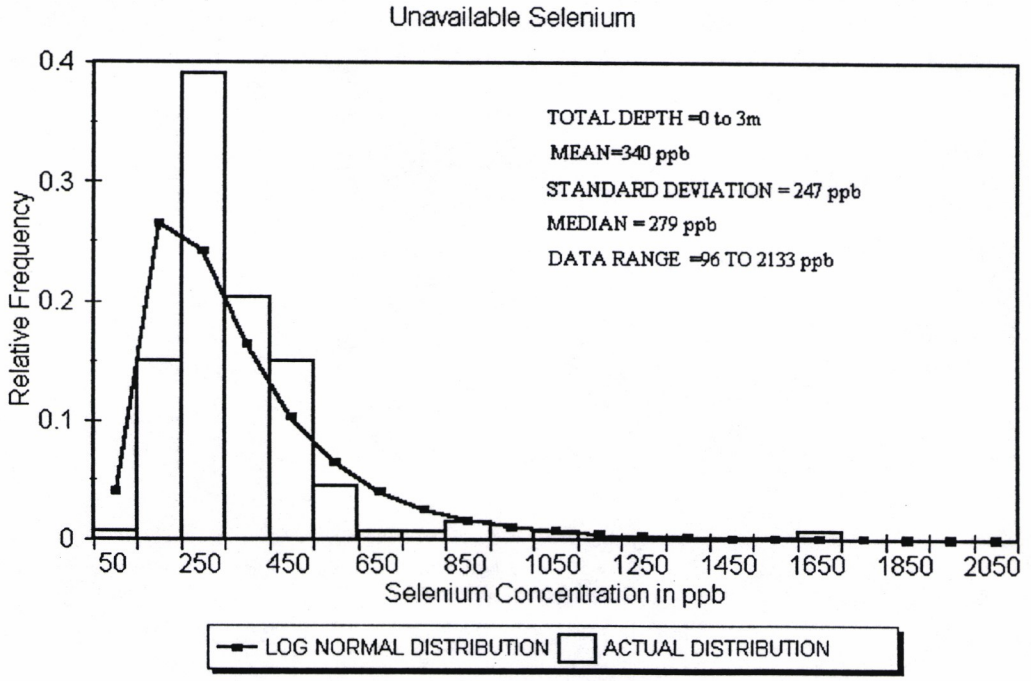

Figure 9. Relative frequency distributions for the 3-m profile, unavailable selenium data set and the representative log normal probability density function.

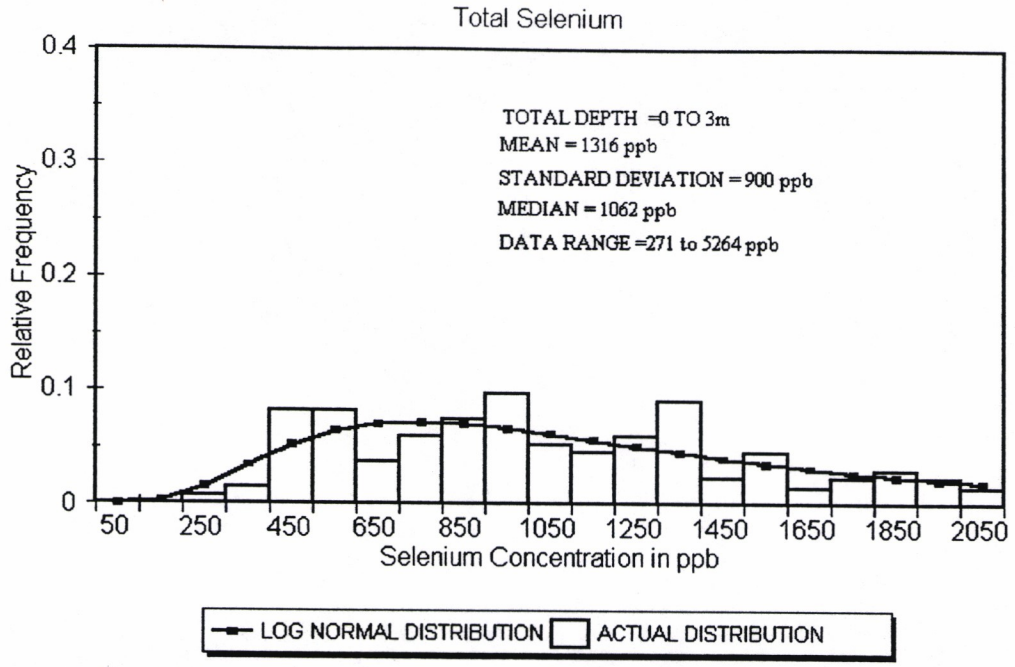

Figure 10. Relative frequency distributions for the 3-m profile, total selenium data set and the representative log normal probability density function.

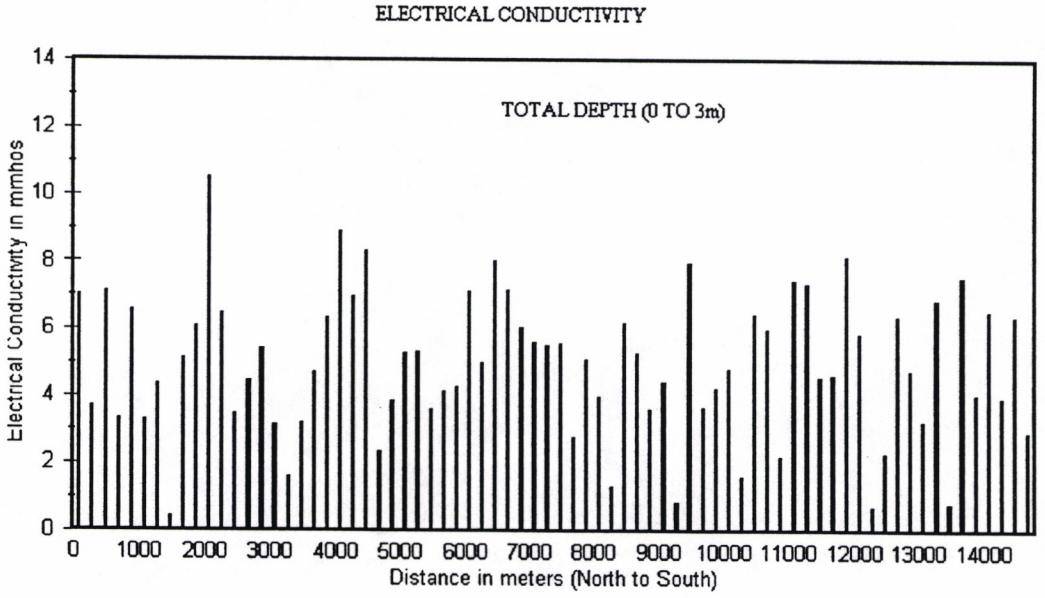

Figure 11. Electrical conductivity (EC) values (mmhos) for the 3-m soil profile along the 16.7-km north to south leg of the transect in the collapsed drift area east of Choteau Creek.

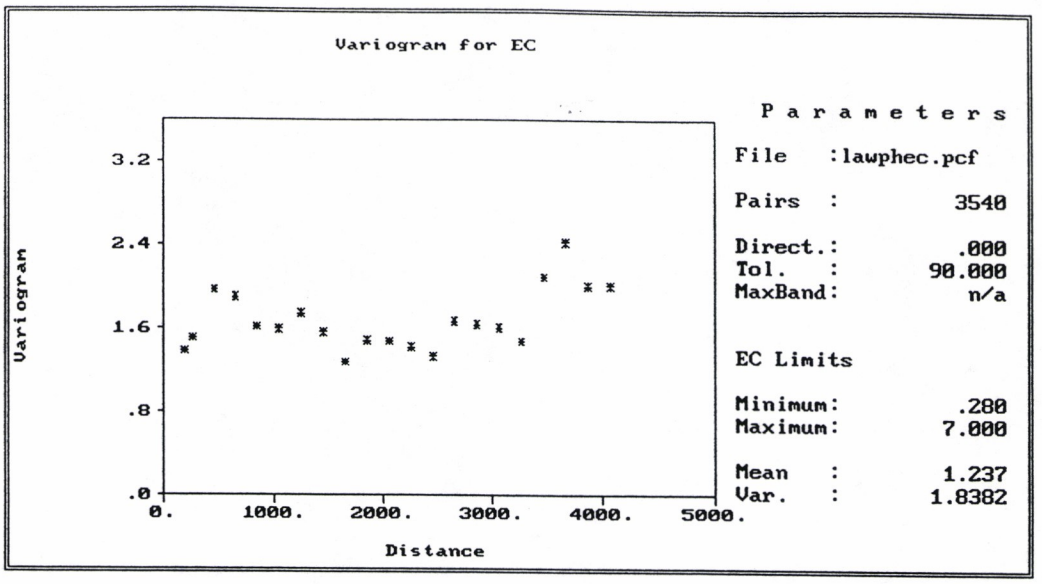

Figure 12. Semi-variogram for the EC values in the top 0.5-m depth of the collapsed drift east of Choteau Creek.

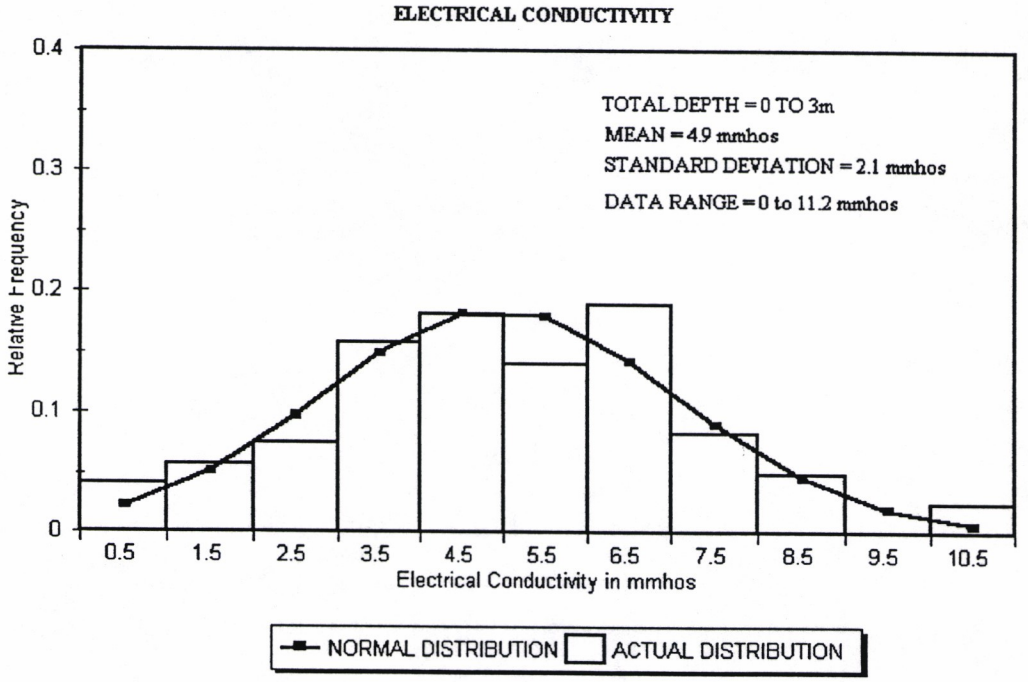

Figure 13. Relative frequency distributions for the 3-m profile, EC data set and the representative normal probability density function.

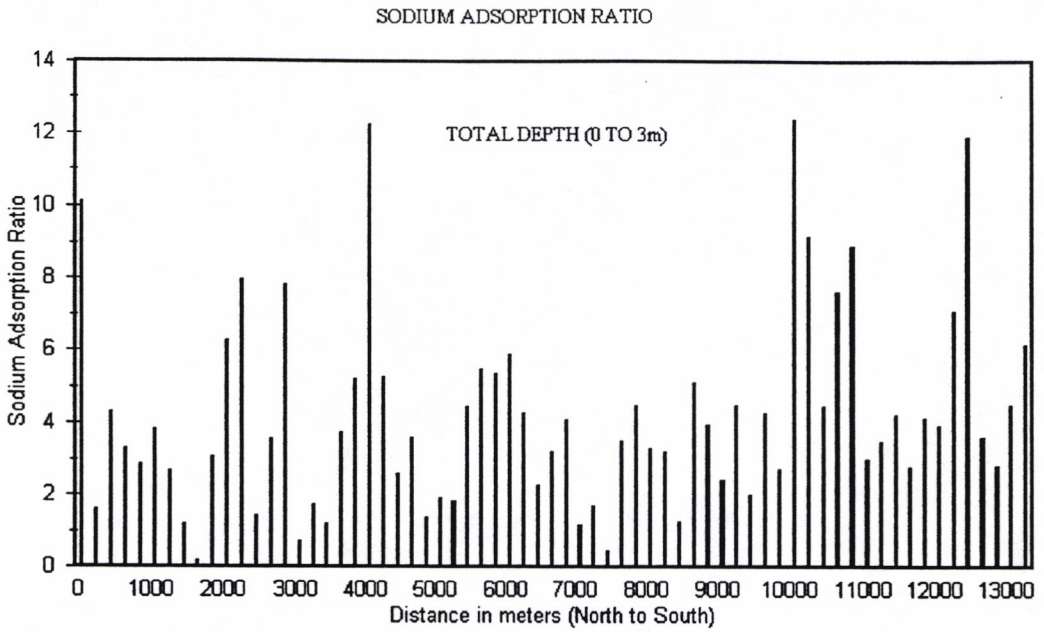

Figure 14. Sodium adsorption ratios (SAR) values for the 3-m soil profile along the 16.7-km north to south leg of the transect in the collapsed drift area east of Choteau Creek.

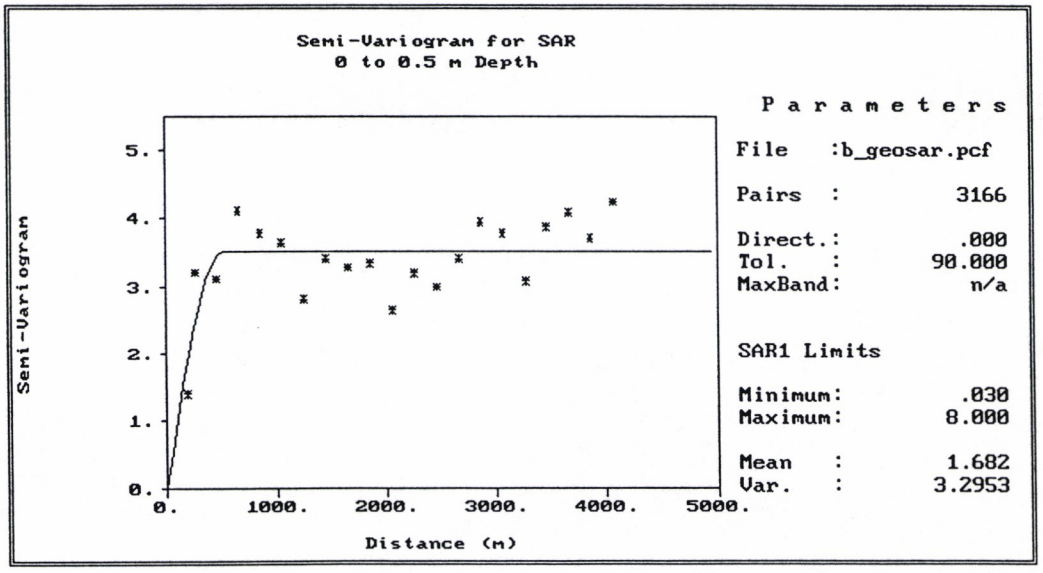

Figure 15. Semi-variogram for the SAR values in the top 0.5-m depth of the collapsed drift east of Choteau Creek.

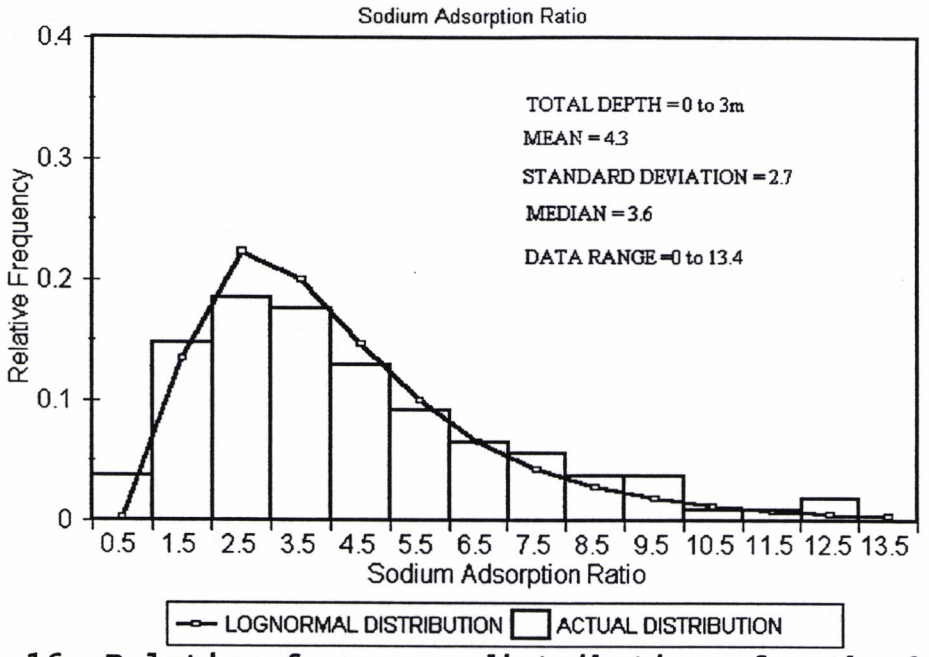

Figure 16. Relative frequency distributions for the 3-m profile, SAR data set and the representative normal probability density function.

SELENIUM CONCENTRATIONS IN SUBSURFACE DRAINAGE WATER

Darrell W. DeBoer[1] and Arthur Warrick[2]

ABSTRACT

A two parameter Gamma Distribution was used to develop a transfer function for the discharge of a solute, in this case selenium, from a subsurface drain line. Statistical relationships were developed to define the relationships between the two distribution parameters and subsurface drainage system geometry. Relationships between changes in drainage area solute concentration and time for three scenarios of drainage system geometries were also developed. Sample calculations were included to illustrate the use of the results.

INTRODUCTION

The Lake Andes-Wagner (hereafter called LAW) project is a proposed 16,000-ha, irrigation project in south central South Dakota. The project area is located adjacent to and east of the Missouri River where the River becomes the border between Nebraska and South Dakota (Figure 1).

Soils investigations in the LAW project area by Breitzman (1990) and Wilson et al. (1990) found selenium concentrations similar to those in the San Joaquin Valley of California where major environmental problems were detected. In addition, earlier drainage investigations of the project area (US Bureau of Reclamation, 1985) indicate that most of the irrigated lands will require subsurface drains to provide adequate subsurface drainage under sustained irrigated conditions. Thus, there is concern about the possibility of elevated selenium concentrations occurring in drainage water from the LAW project if it is constructed. Current data sets provide insight into the range of selenium concentrations that can be encountered in the field but there is a need to get a "feel" for the selenium concentrations that can be expected from subsurface drainage systems over time.

The objective of this study is to develop an estimate of selenium concentrations that can be expected in drainage water if subsurface drainage systems are installed in the LAW Project area.

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PROGRESS REPORT

Drain Spacing Distribution

Saturated hydraulic conductivities of soils east of Choteau Creek were measured and reported by the US Bureau of Reclamation (1985). The hydraulic conductivity data set has a mean of 3.7 cm/h, a standard deviation of 5.0 cm/h, a median of 2.0 cm/h and appears to follow a log normal frequency distribution (Figure 2).

An irrigation water management analysis was preformed for the soil and climatic conditions of the LAW Project area. A relationship was developed between drain line spacings that would satisfy a minimum water table depth requirement of 1.2 m during the year and saturated hydraulic conductivity values.

$$S = (4972*K - 783*K^2 + 53.8*K^3)/100 \qquad (1)$$

where S = drain line spacing (m) and
K = hydraulic conductivity (cm/h).

A frequency distribution of estimated drain line spacings for the area east of Choteau Creek was developed by transforming hydraulic conductivity values of less than 6.5 cm/h (Figure 2) into drain line spacings values with the aid of equation 1 (Figure 3). Again the drain line spacing data set appears to follow a log normal frequency distribution. Similarly, reciprocal (1/S) values follow a log normal frequency distribution. The reciprocal drain line spacing distribution will be used in the following selenium discharge analysis.

Saturated Travel Time

An analytical solution of saturated water flow to subsurface drain lines for steady state conditions was presented by Kirkham (1958). The solution is valid for conditions where drain lines are uniformly spaced, a homogeneous soil profile exists and an impermeable barrier is located below the drain lines (Figure 4.)

Computation of travel times for water flow in the saturated soil region below the drain line was accomplished in two steps. First, a gradient search method was used to trace streamlines described by a stream function as presented by Kirkham and Powers (1972). The gradient search method identified the coordinates in the soil profile through which the streamlines passed. The second step of the travel time computation was to determine the convective velocity at each coordinate and then use the time equals distance divided by rate relationship to calculate the time for water to flow along each increment of the stream line. Total travel time in each stream tube was the sum of all travel times for all stream line increments. The travel times agreed with those presented by

Jury (1975) and Utermann et al. (1990). These travel times represent a first approximation for actual field values because it is assumed that piston or bulk water flow controls the movement of a solute and that the influence of diffusion, dispersion and soil reactions are not important.

A graphical representation of relationships between dimensionless travel time ($Rt/\theta S$) and discharge concentration (C/Co) for five drainage system geometries (S/D ratios ranging from 1 to 40) is presented in Figure 5. R is the mean flux rate, t is time, θ is the saturated soil water content and S is the half spacing between drains. This analysis assumes an initial soil solute concentration of C with a step increase of solute concentration to Co at time zero. The C/Co ratio can be replaced by a dimensionless distance (x/S) which represents the horizontal distance from the drain line as illustrated by Jury (1975).

Transfer Function

As was done by Utermann et al. (1990), a two parameter Gamma Distribution can be used to describe the dimensionless travel times through the saturated zone.

$$F(\alpha,\beta,t) = (\beta/\Gamma(\alpha+1))(\beta t)^{\alpha}\exp(-\beta t) \qquad (2)$$

The concentration at time T for a step input is

$$C(T)/Co = \int_0^T F(\alpha,\beta,\tau)\,d\tau \qquad (3)$$

Dimensionless time and concentration ratio values were obtained from Figure 5 for a given S/D value and plotted as data values (Figure 6). A steepest decent numerical method along with trial and error were used to estimate the α and β parameter values for the data set until the r^2 value for the fitted Gamma Distribution was more than 0.99. The α value for the S/D equal to 5 data set in Figure 6 is -0.12 and the corresponding β value is 5.0. Likewise, the α value is 0.0 and the β value is 41.0 for the S/D equal 40 data set (Figure 7). This same procedure was performed on all of the S/D data sets and then the α, β and S/D data set was used to define relationships for α and β in terms of S/D values.

A quadratic interpolating function was used to represent the α parameter as a function of D/S (note the use of a reciprocal) (Figure 8)

$$\alpha(D/S) = 0; \quad D/S \leq 0.04 \qquad (4)$$

$$\alpha(D/S) = -0.006 + 0.273(D/S) - 4.256(D/S)^2; \quad D/S > 0.04 \qquad (5)$$

while a power interpolating function was used for the β parameter (Figure 9).

$$\beta(D/S) = 1.1245(D/S)^{-0.9789} \qquad (6)$$

Ten D/S data values ranging from 0.025 to 0.20 were used to generate the interpolating functions.

Monte Carlo Simulation

A Monte Carlo simulation designed to represent drainage from "n" drains in a region was conducted. A single drain D/S value was randomly selected from a log normal distribution with a mean D/S value of 0.1 and a coefficient of variation of 0.05, 0.5 or 1.0. Second, α and β parameter values were estimated from equations 4, 5 and 6. Third, the transfer function was defined by substituting the α and β parameter values into the Gamma Distribution (equation 2). Fourth, a random solute concentration value was selected from a normal distribution with a mean of 1.0 and a standard deviation of 0.1. Fifth, the transfer function was multiplied by the solute concentration to obtain the drain flow concentration. These five steps were repeated for 1000 drains and the outputs were summed and normalized to obtain relationships between drain discharge concentration and dimensionless time (Figure 10).

Unsaturated Travel Time

All results to this point have been for flow in the saturated zone only. A common assumption is to assume vertical flow in the unsaturated zone above the water table which allows one to estimate the travel time in the unsaturated zone as

$$t_{unsat} = (\theta/R)(h - D) \qquad (7)$$

Where t_{unsat} = unsaturated travel time
θ = unsaturated soil water content and
h = depth to the impermeable layer

The unsaturated flow time was not used in the Monte Carlo simulation because it was assumed that the water table was at a constant depth. To obtain total travel time for the drains, the unsaturated travel time must be added to the saturated travel time.

Sample Calculations

Assume a drain depth of 2.1 m, an impermeable layer depth of 4.6 m and a drain spacing of 50 m. Then D = 4.6 - 2.1 = 2.5 m and D/S = 2.5 m/25 m = 0.1. Note the S value is one half the drain spacing. Also assume annual recharge rate of drain discharge of 2.5 cm/yr and a soil porosity of 0.5. Now

$$T = (Rt)/(\theta S) \quad \text{or} \quad t = \theta ST/R = 0.5(2500)T/2.5 = 500T$$

where t has units of years.

The drain spacing data in Figure 2 has a coefficient of variation (CV) equal to about 0.6. The line representing a CV value of 0.5 in Figure 10 will be used in this example.

If we consider a leaching mode of operation where the system starts with an initial solute concentration of Co and decreases to C, then the value of 1 - C(T)/Co is meaningful for us because it represents the decrease in solute concentration over time.

Selecting values of C/Co from Figure 10 for corresponding values of T, we get the following data sets for two conditions where real time is equal to 500T and 250T.

T	C/Co	1 - C/Co	t = 500T	t = 250T
0.01	0.216	0.784	5.0 yr	2.5 yr
0.02	0.320	0.680	10.0	5.0
0.03	0.400	0.600	15.0	7.5
0.05	0.517	0.483	25.0	12.5
0.10	0.691	0.309	50.0	25.0
0.20	0.847	0.153	100.0	50.0
0.40	0.952	0.048	200.0	100.0

A plot of the data sets shows an increase in drain discharge, R, or a decrease in drain spacing, S, causes the solute concentration to decrease faster over time (Figure 11). Any combinations of θ, R or S that cause the value of $\theta S/R$ to increase will extend the field time that it takes for a given concentration level to be obtained. The relationships in Figure 11 indicate that it will take about 12.5 years for the solute concentration to be reduced to 50 % of its original value for the "250 T" data set and 25 years for the "500 T" data set.

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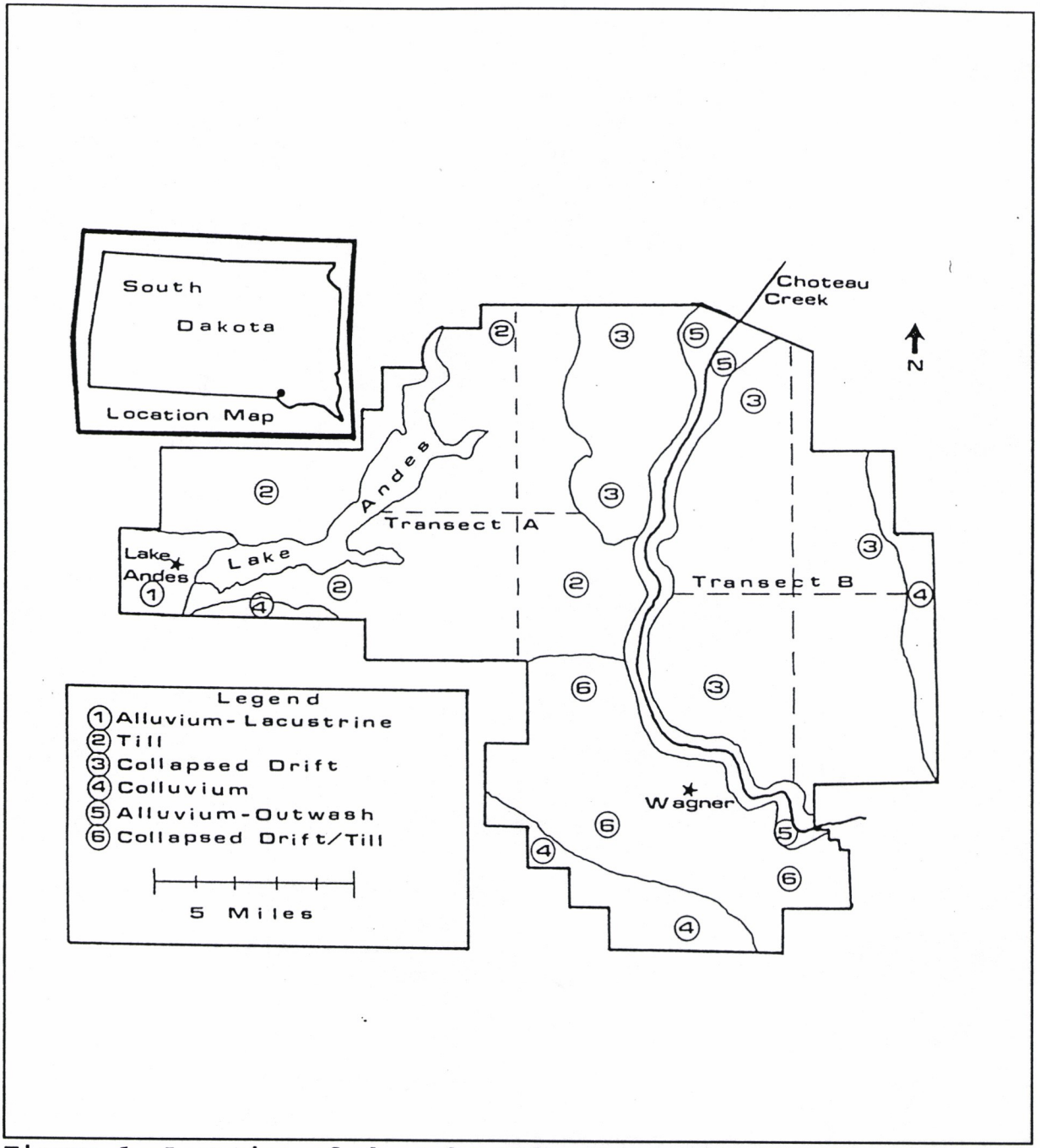

Figure 1. Location of the Lake Andes-Wagner Project area in south central South Dakota.

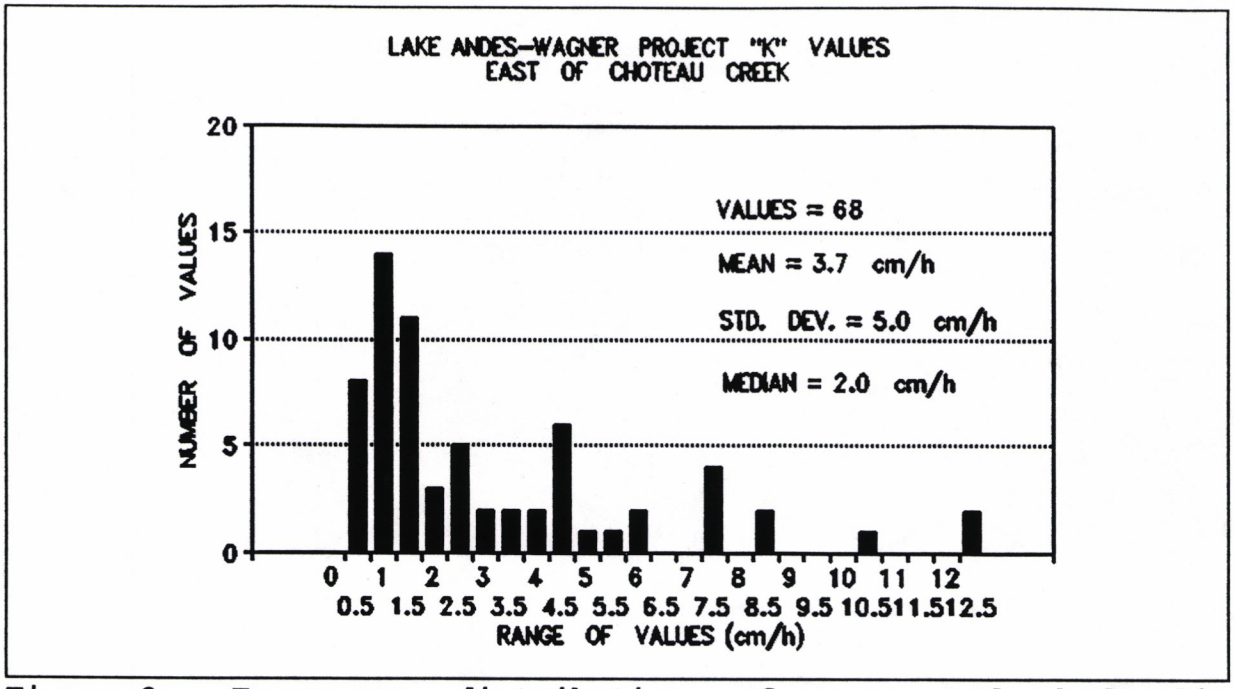
LAKE ANDES-WAGNER PROJECT "K" VALUES
EAST OF CHOTEAU CREEK
NUMBER OF VALUES
20
15
10
5
0
VALUES = 68
MEAN = 3.7 cm/h
STD. DEV. = 5.0 cm/h
MEDIAN = 2.0 cm/h
0 1 2 3 4 5 6 7 8 9 10 11 12
0.5 1.5 2.5 3.5 4.5 5.5 6.5 7.5 8.5 9.5 10.5 11.5 12.5
RANGE OF VALUES (cm/h)

Figure 2. Frequency distribution of saturated hydraulic conductivity values for soils east of Choteau Creek.

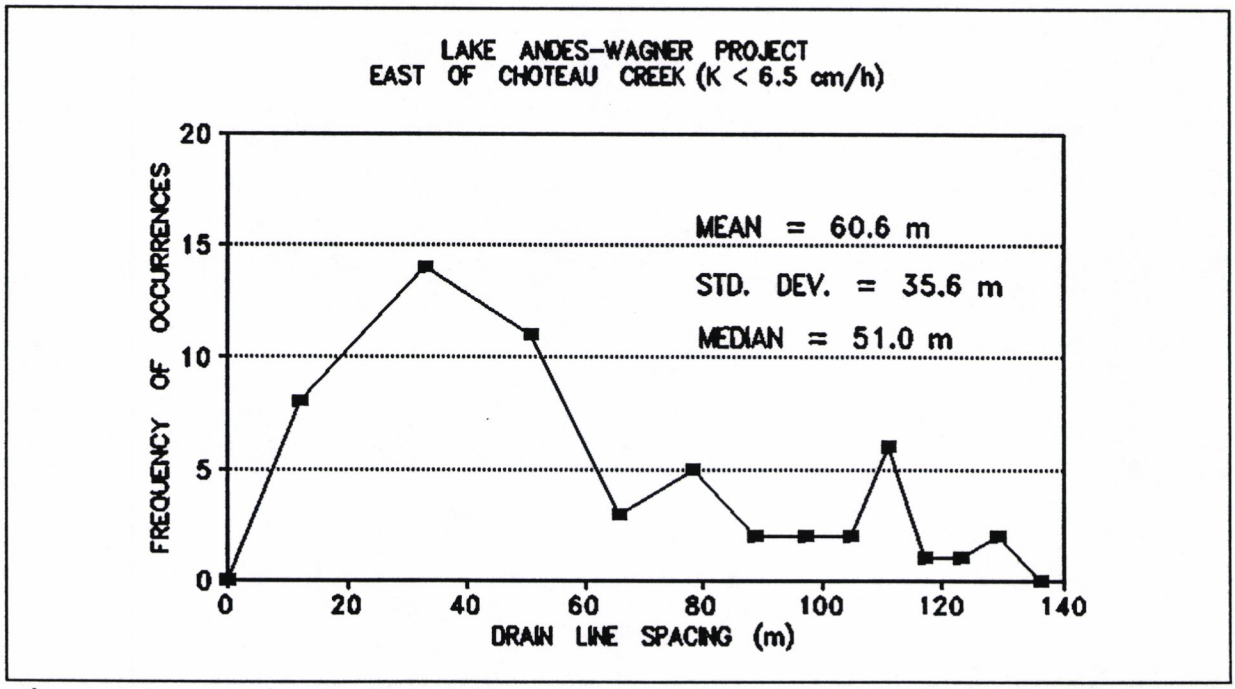

Figure 3. Estimated frequency of drain spacing values based on the distribution of saturated hydraulic conductivities.

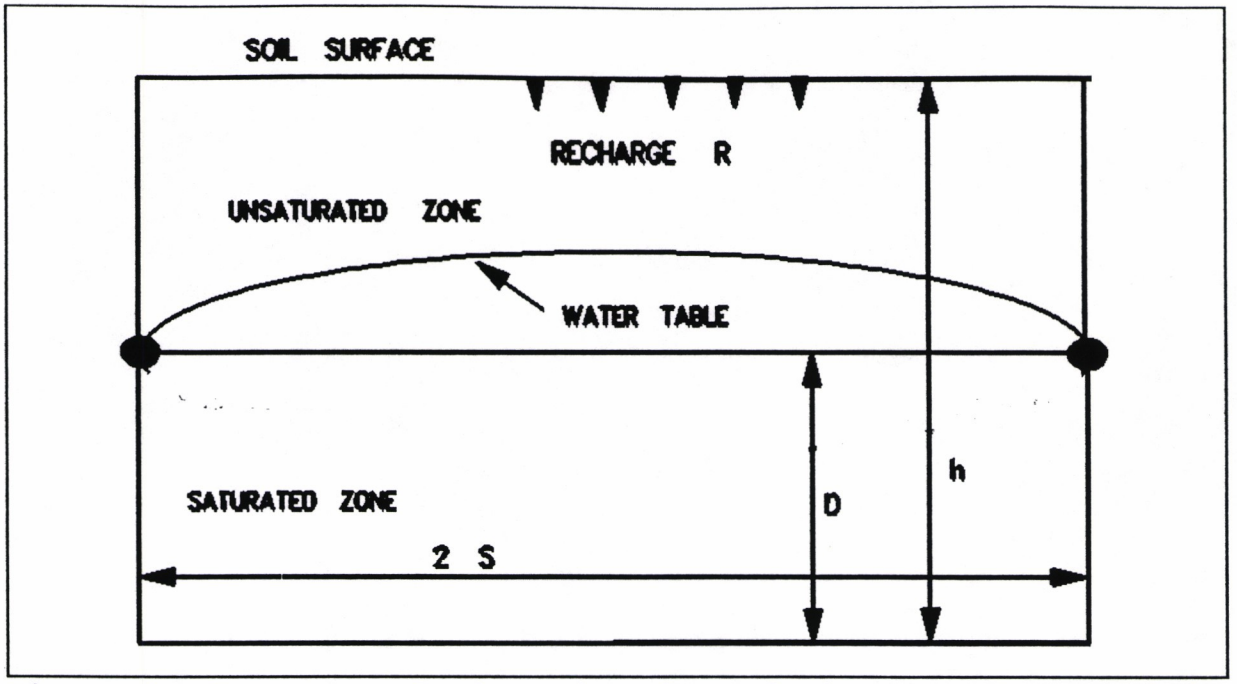

Figure 4. Geometry of the subsurface drainage system used by Kirkham (1958).

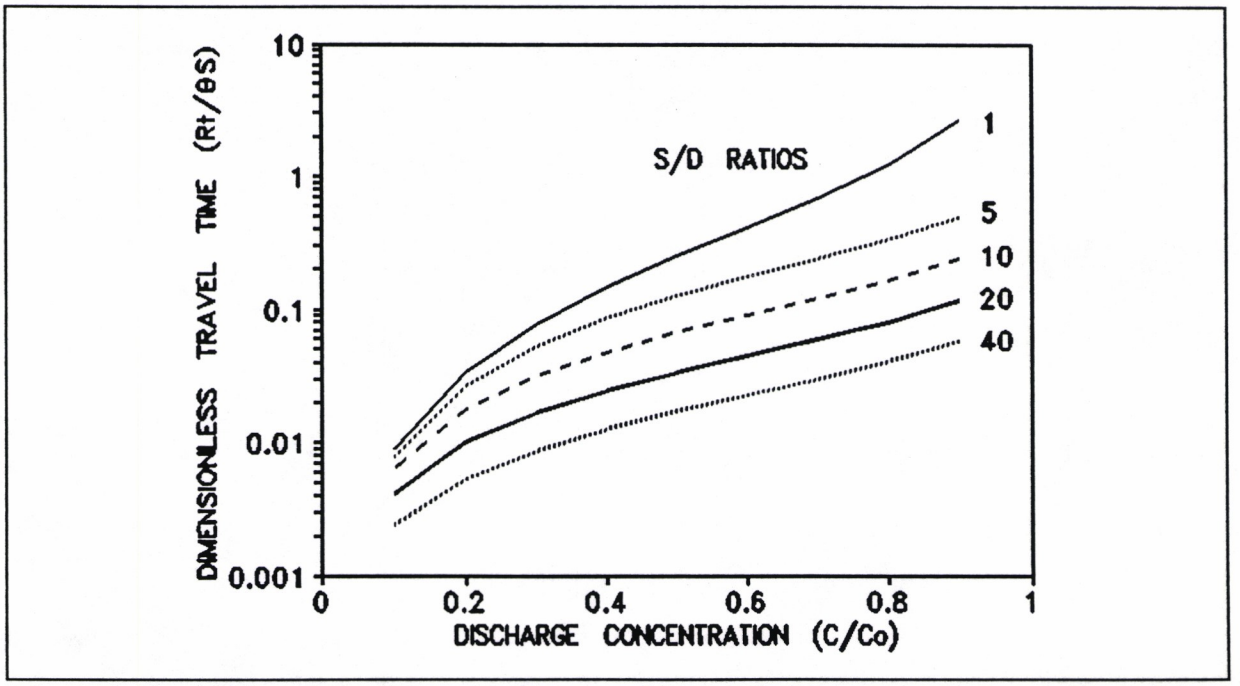

Figure 5. Relationship between dimensionless time and solute concentration of discharge from a subsurface drain.

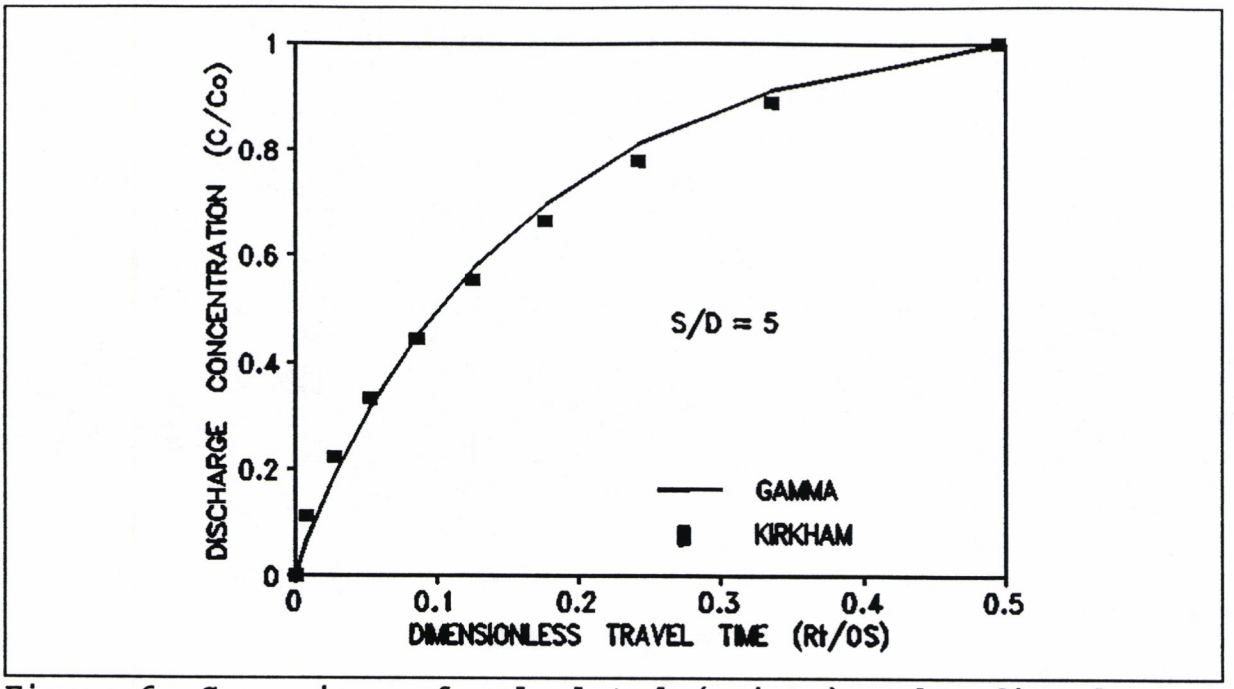

Figure 6. Comparison of calculated (points) and a fitted Gamma Distribution (line; alpha = -0.12, beta = 5.0) for S/D of 5.

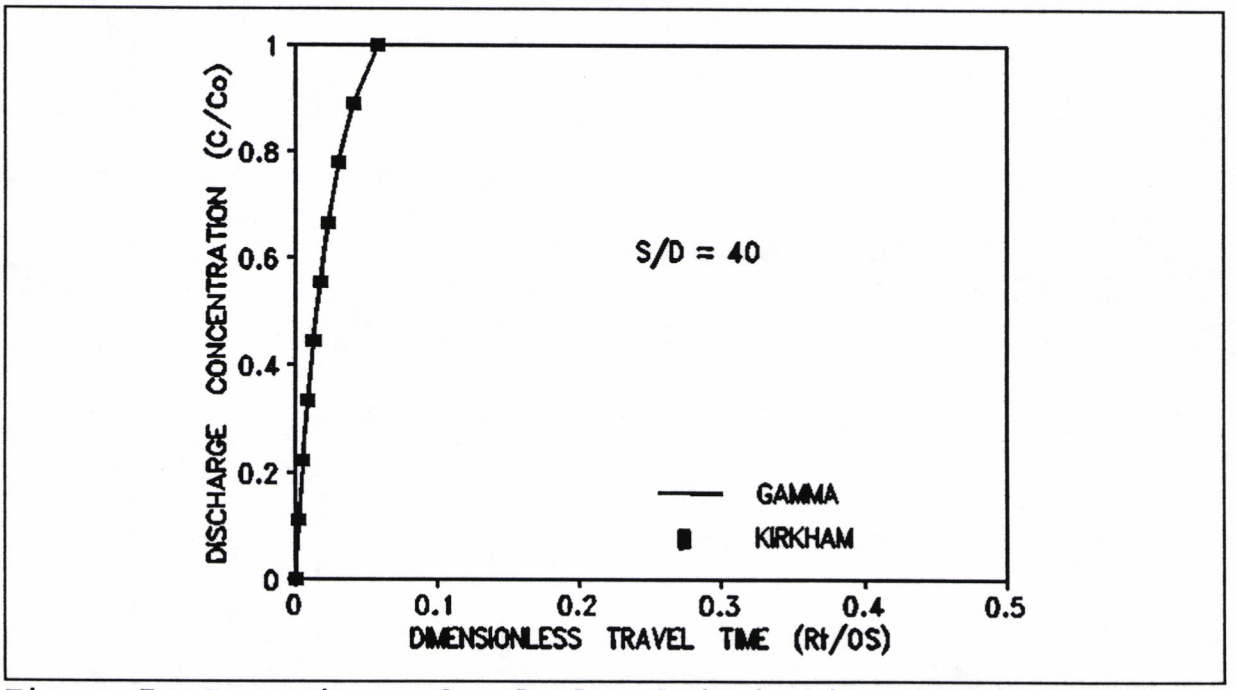

Figure 7. Comparison of calculated (points) and a fitted Gamma Distribution (line; alpha = 0, beta = 41.0) for S/D of 40.

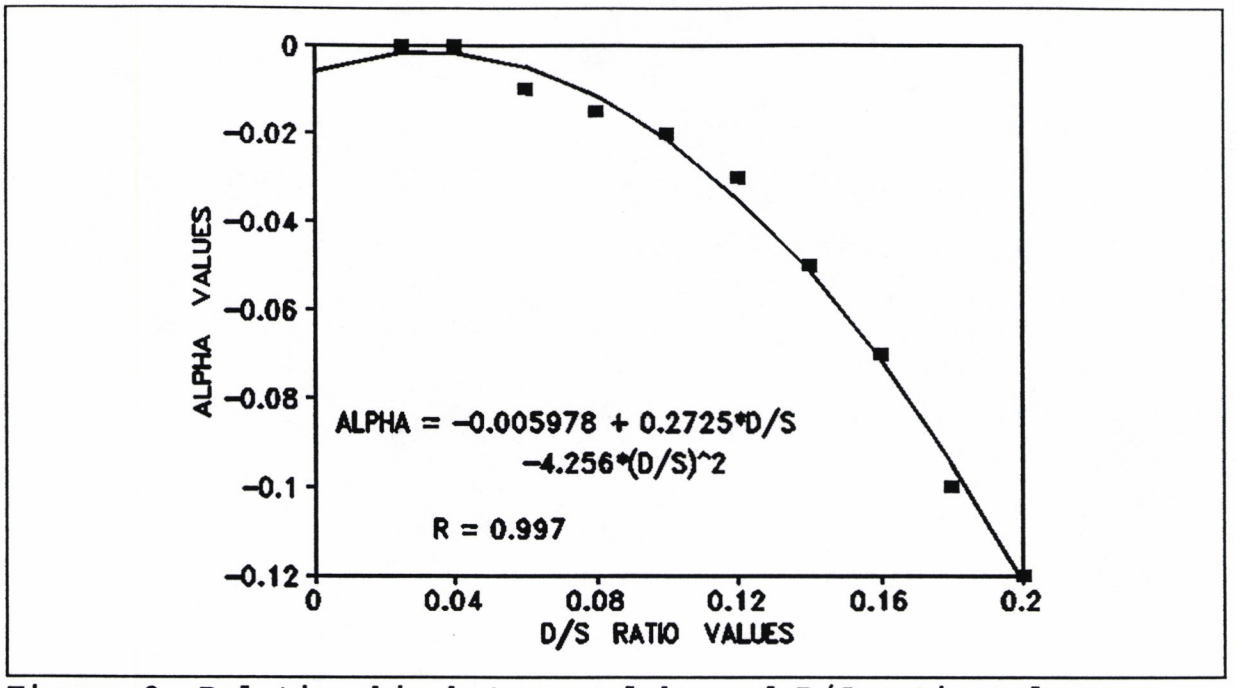

Figure 8. Relationship between alpha and D/S ratio values.

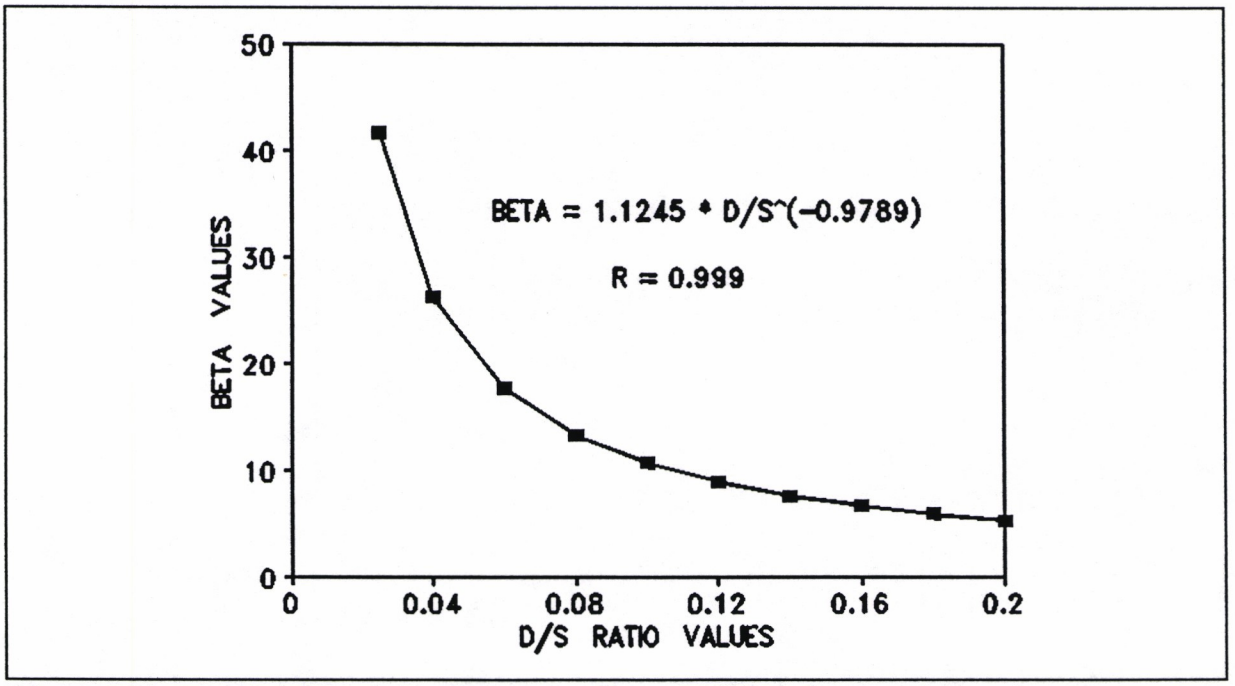

Figure 9. Relationship between beta and D/S ratio values.

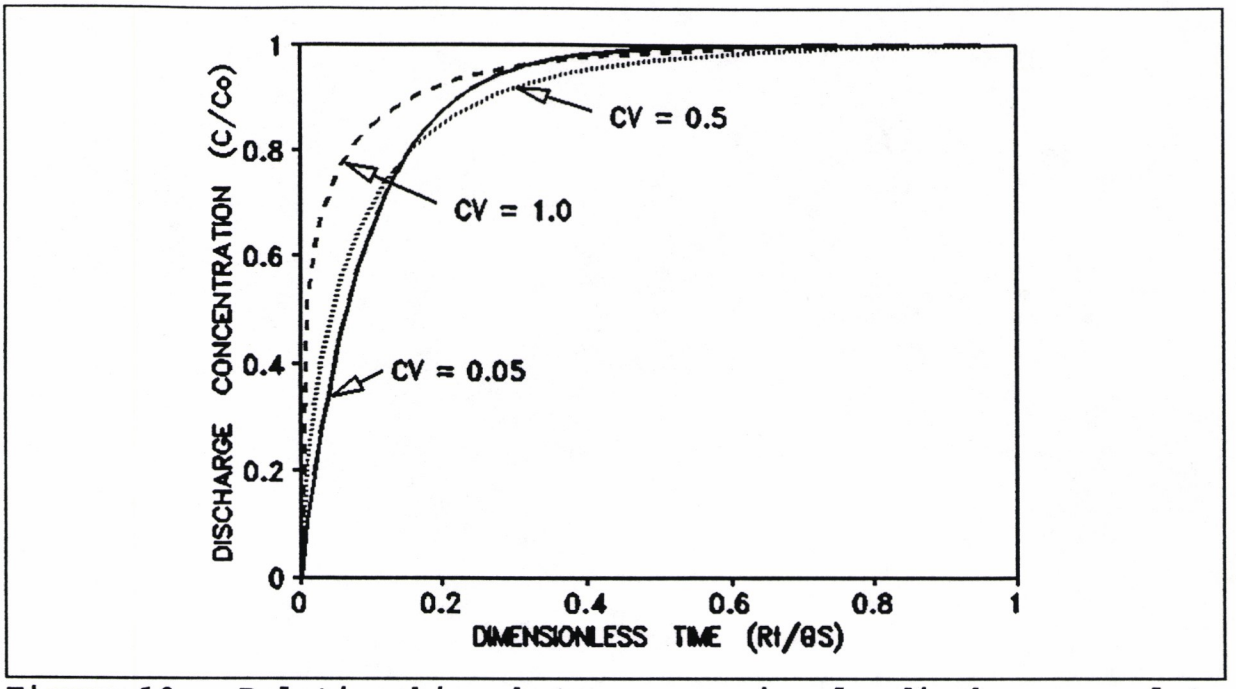

Figure 10. Relationship between regional discharge solute concentration and dimensionless time for a log normal distribution of D/S values with CV values of 0.05, 0.5 and 1.0.

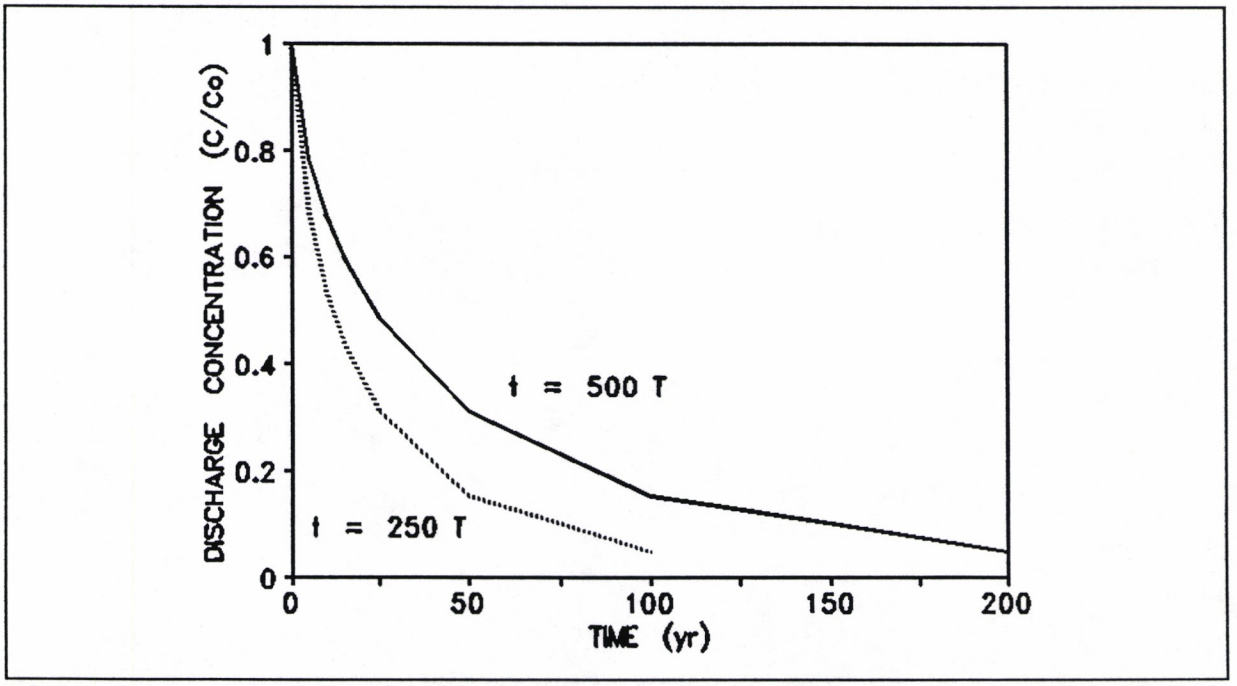

Figure 11. Change in solute concentration over time for a drainage system when leaching of the soil profile occurs.